First Flames:
Burning, Turbulence and Buoyancy

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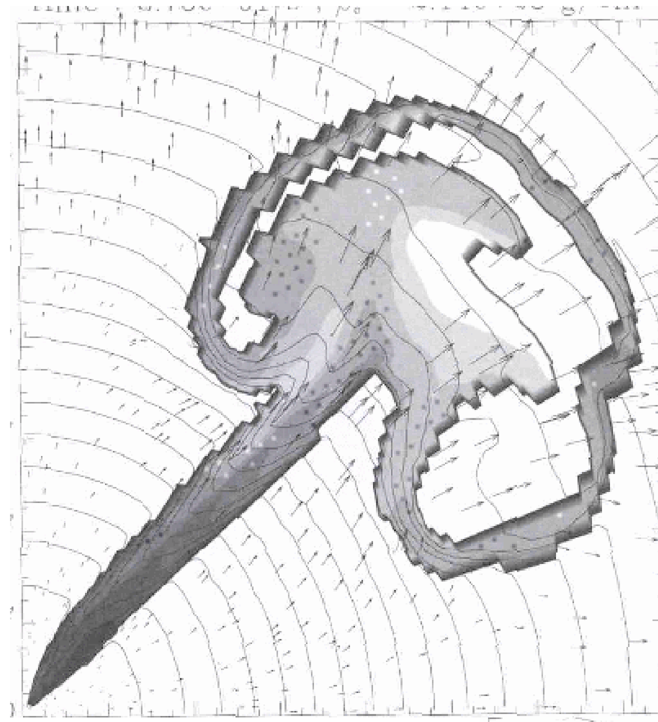
Flame Ignition

Nigel Gorbold, Univ. Colorado

- Highly nonlinear, transient phenomenon
- Interaction of nuclear reactions, conductivity, hydrodynamics
- Difficult to model

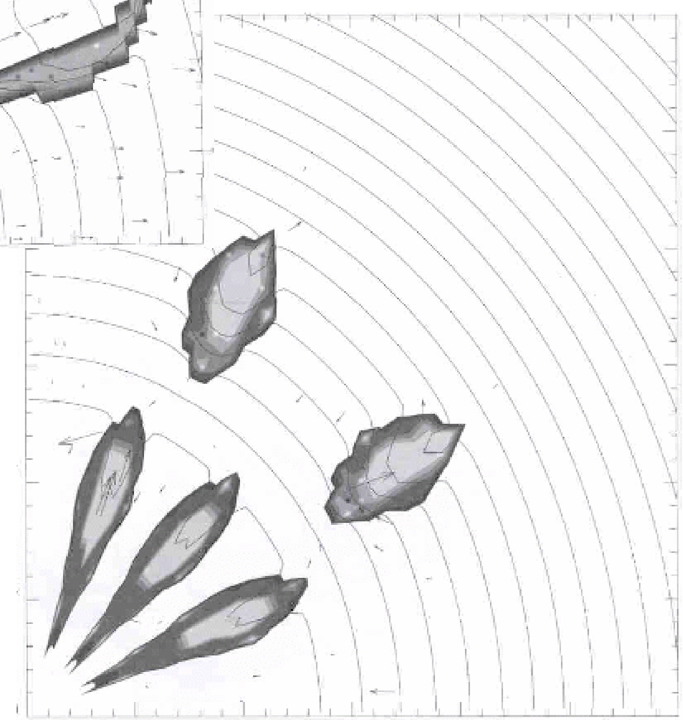
Ignition

- Turbulent conditions
- Many potential `flashpoints’
- Important to understand where/ when points do ignite

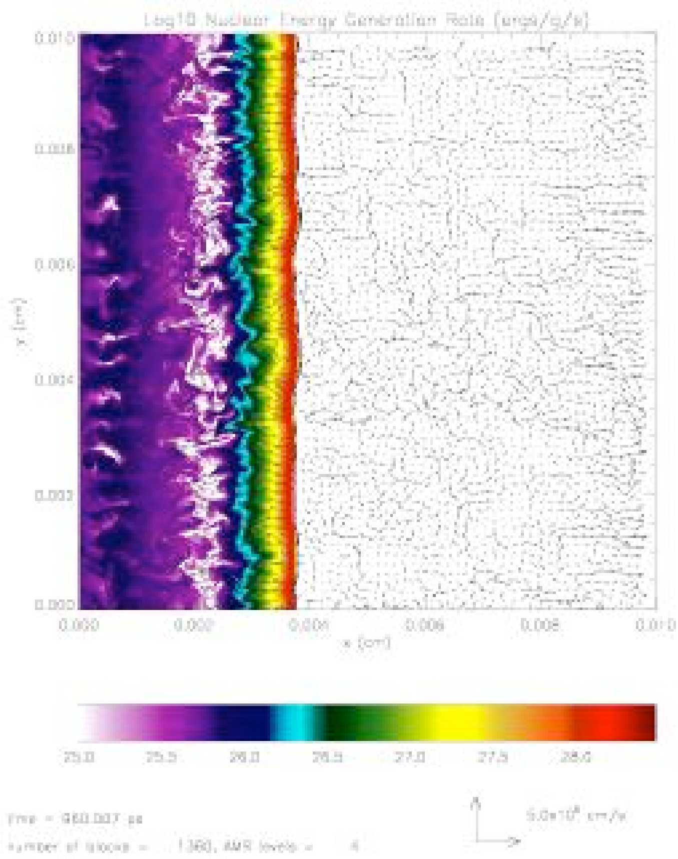


Niemeyer, Hillebrandt & Woosley (1996):

success of explosion can depend sensitively on number, location of ignition points



Early Burning



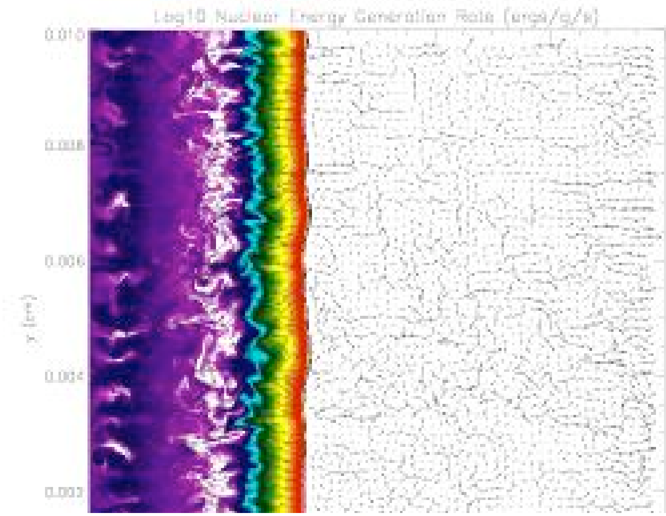
- Ignition can occur on ~cm scales
    - Not resolved by large-scale simulation
- For initial conditions in large-scale simulations, need to map
    - turbulence $\longrightarrow$ ignition points
    - ignition $\longrightarrow$ early flame bubbles

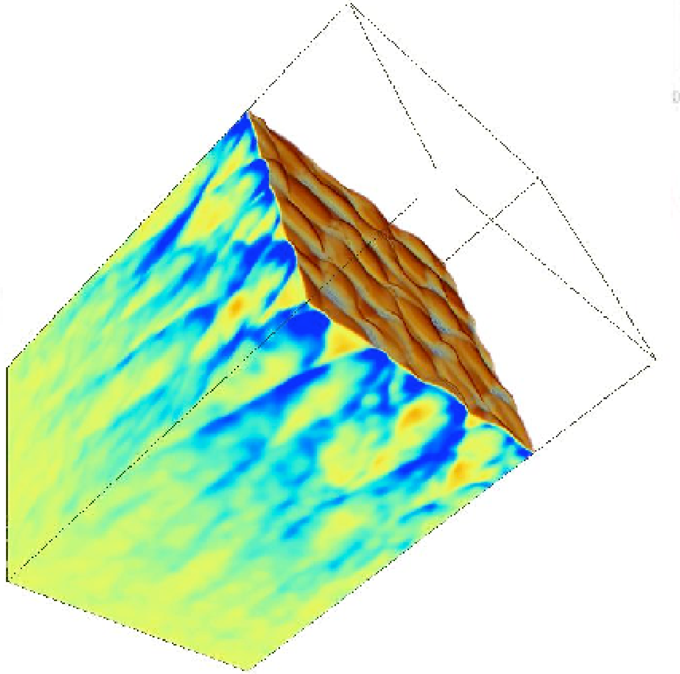
Outline

- Some notes on ignition
  - One-zone
  - Flame (ongoing)
  - Detonation
- Early burning: what happens next?
  - Characteristic size of flame bubbles
  - Flame model?

Flame vs Detonation

- Flame/Deflagration
  - Subsonic
  - Heat propagates by conduction
- Detonation
  - Supersonic
  - Shock-driven heating





Our contributions

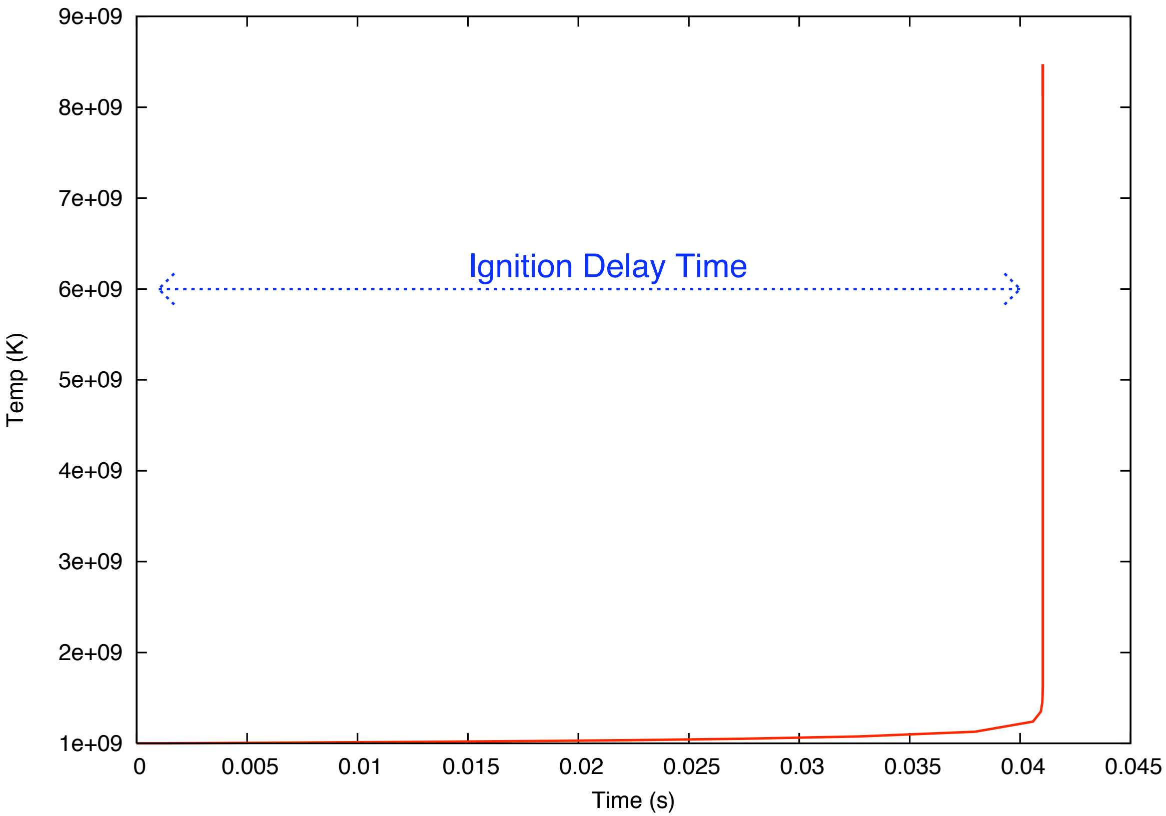
- Dursi & Timmes 2006:
  - One-zone ignition times
  - Very hard to ignite det^n at low densities: need much more than local supersonic flow. Geometric constraint.

Our contributions

- Zingale & Dursi 2007:
  - Under given conditions, there is a characteristic size of a flame bubble - larger is shredded by motions, turbulence
  - This characteristic size may lead to new flame model

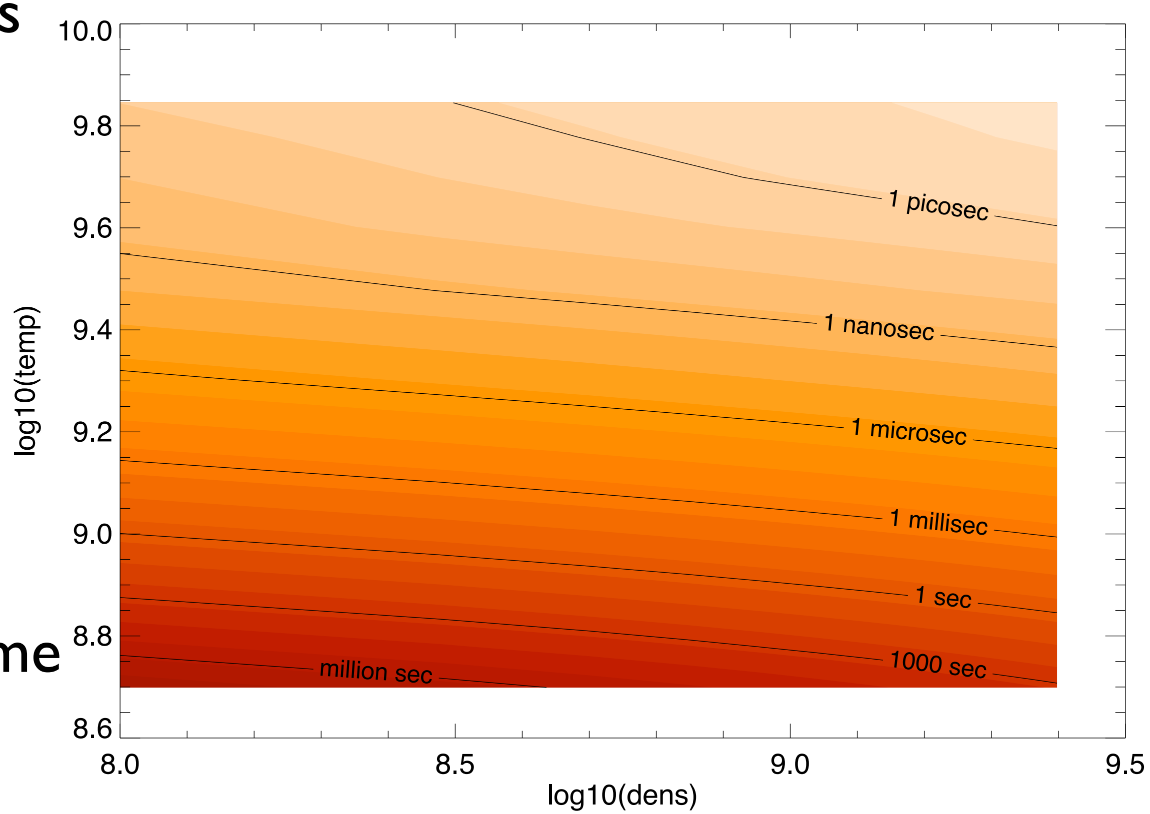
One-zone ignition

- Ignition: interaction of:
    - `chemistry'
    - hydrodynamics
    - conduction
- Even in one-zone model (no hydro, cond^n) not trivial



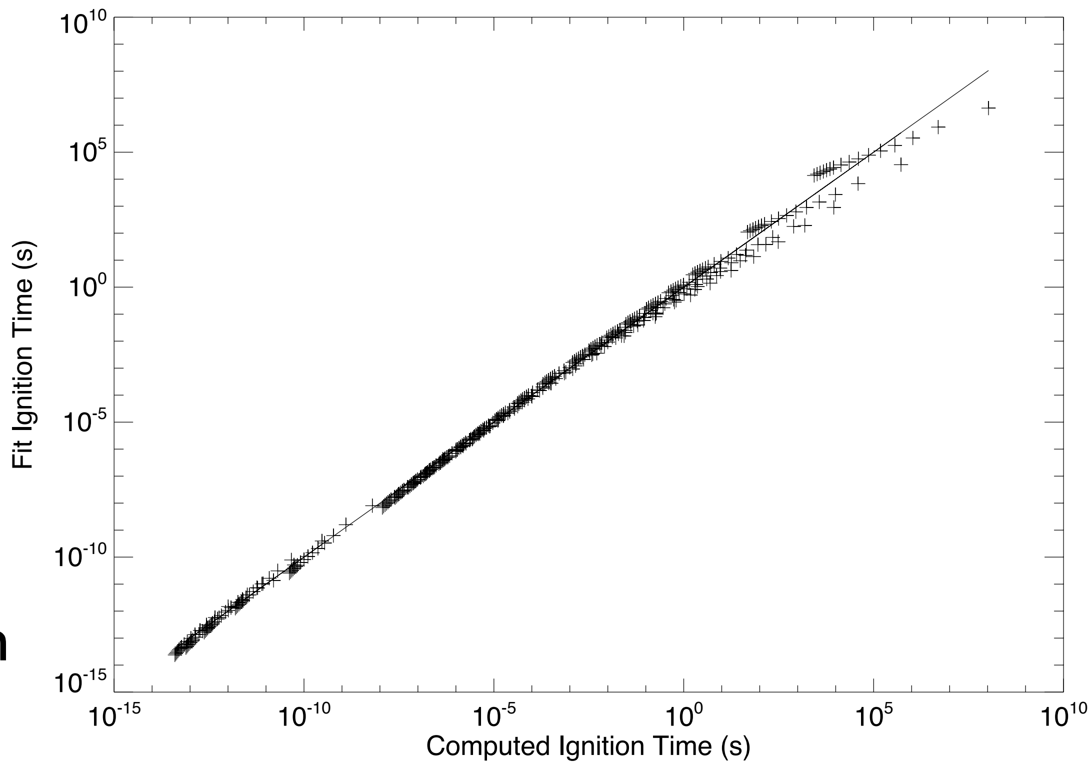
One-zone ignition

- `map out' ignition times for various conditions
- Density, temp, comp.
- Measurement of a `burning time'
  - ignition if burning time faster than flow, conduction times



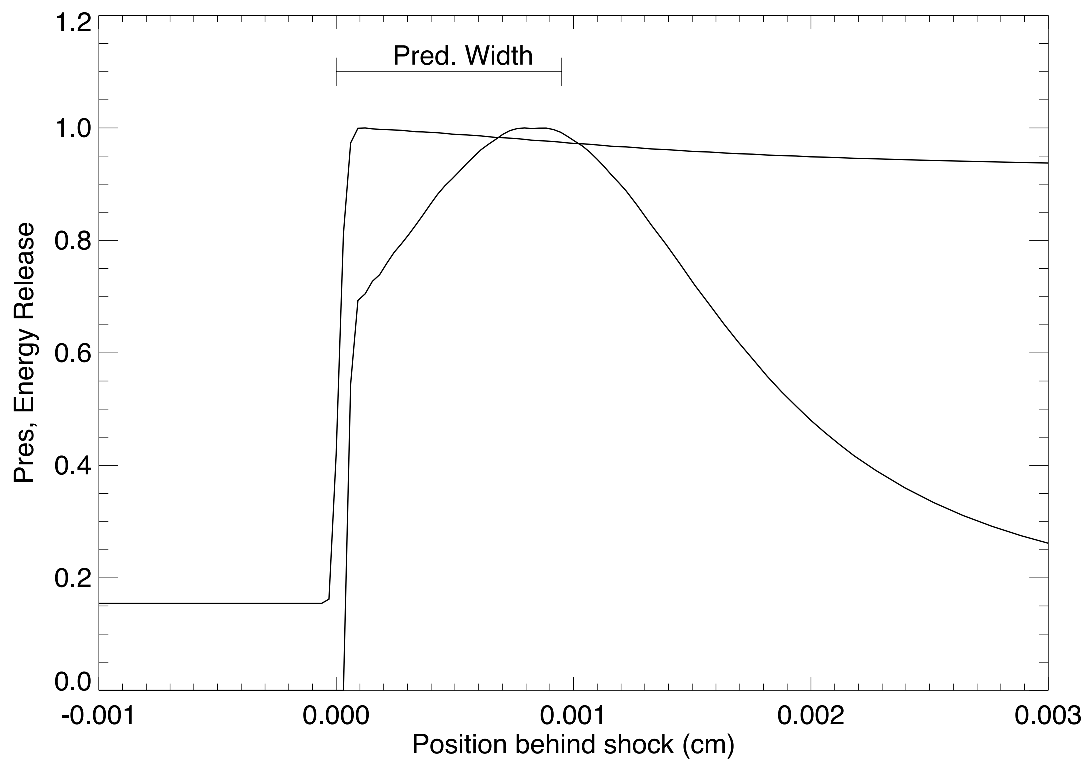
One-zone ignition

- ~7000 calculations
- Can build ignition time fitting function
- Quite good over ~15 orders of magnitude in ignition time
- Surprising dependence on composition - eg, even modest amount of Ne



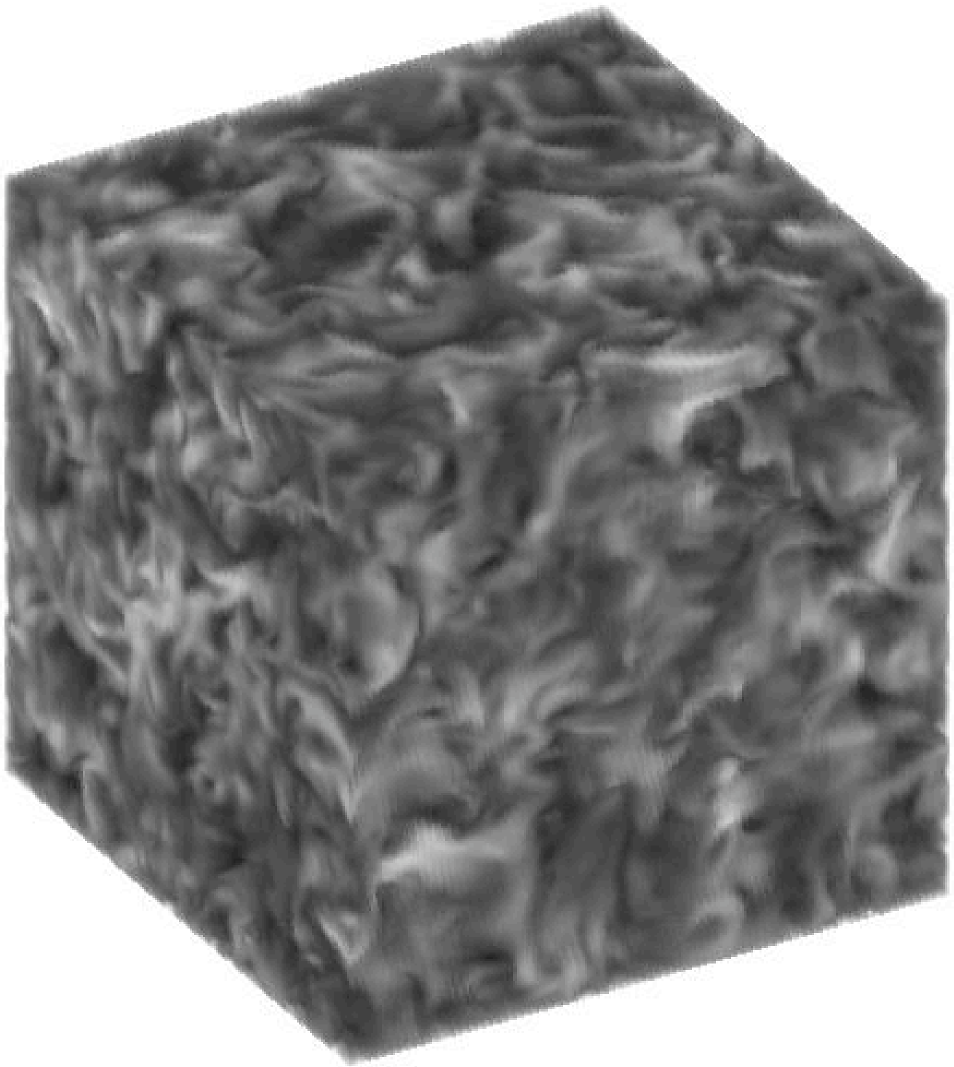
One-zone ignition time

- Necessary input into ignition models
- Ignition time τ_i must be compared to flow (τ_h) and conduction (τ_c) time scales
- Also directly gives detonation thickness - distance behind shock where burning occurs



Flame ignition

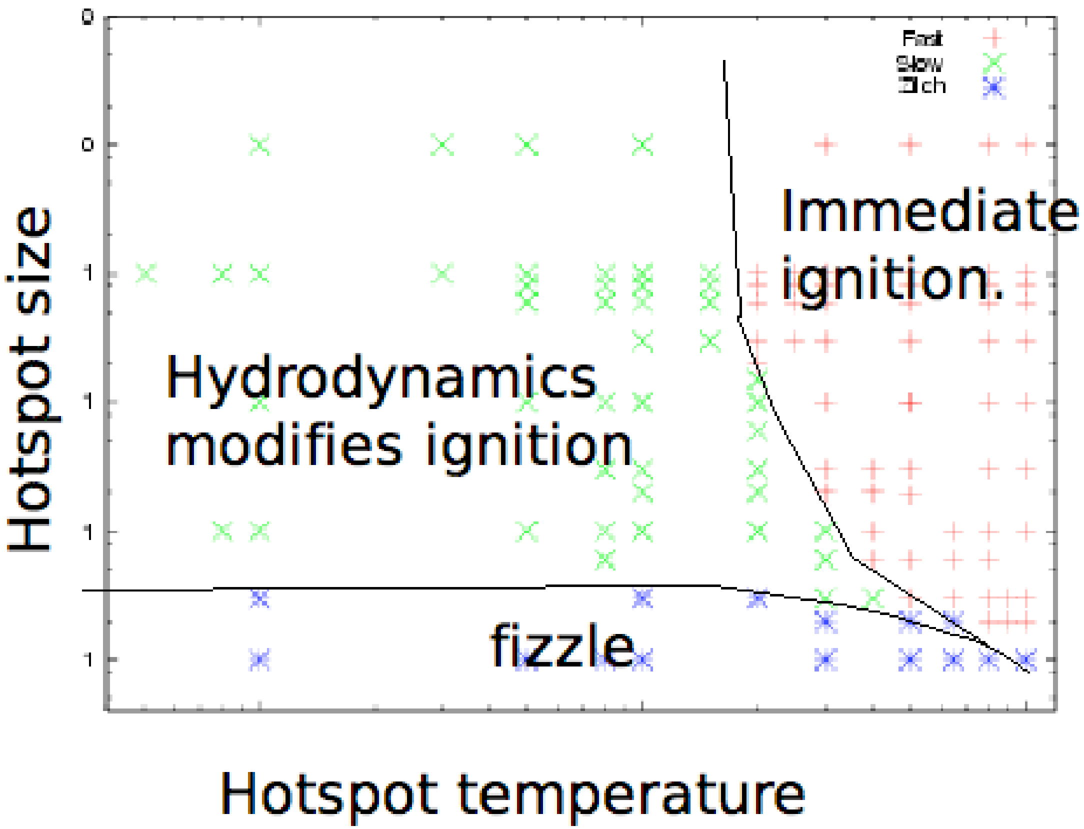
- Only a small part of the question we really want answer to:
- Given a particular turbulent hotspot, can that point ignite before eddies/conduction diffuse it away?



Spark-ignited counterflow flames:
Mastorakos, Marchione, Ahmed, Balachandran, Cambridge

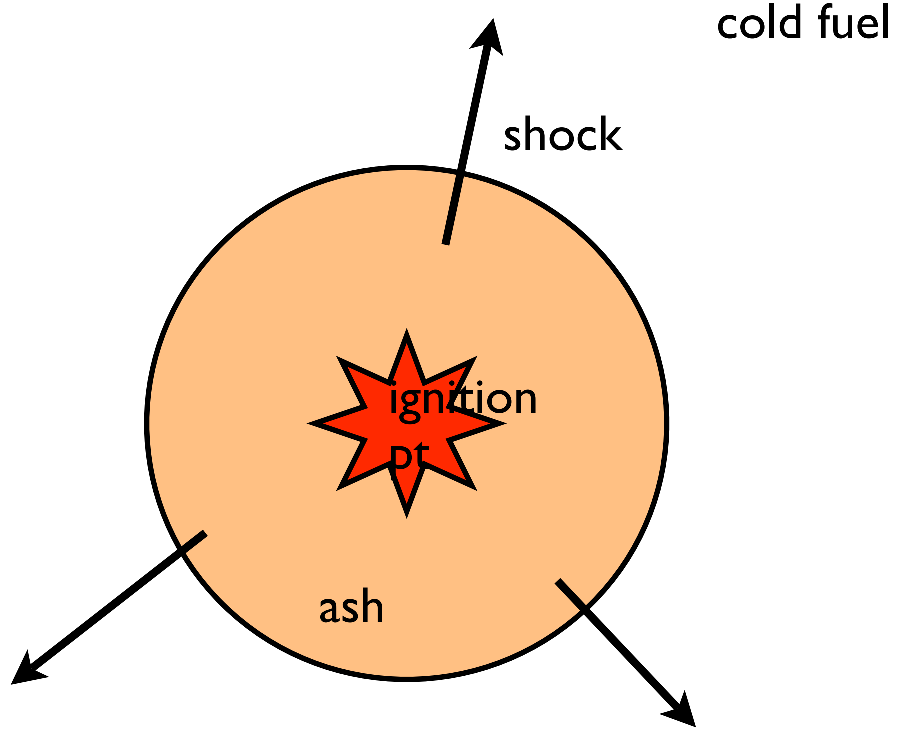
Flame ignition

- Simplified setup:
- Spherical gaussian hotspot, quiescent flow
- Even still, huge parameter space
- Work with undergraduate students Doucette, Hiratsuka, ongoing



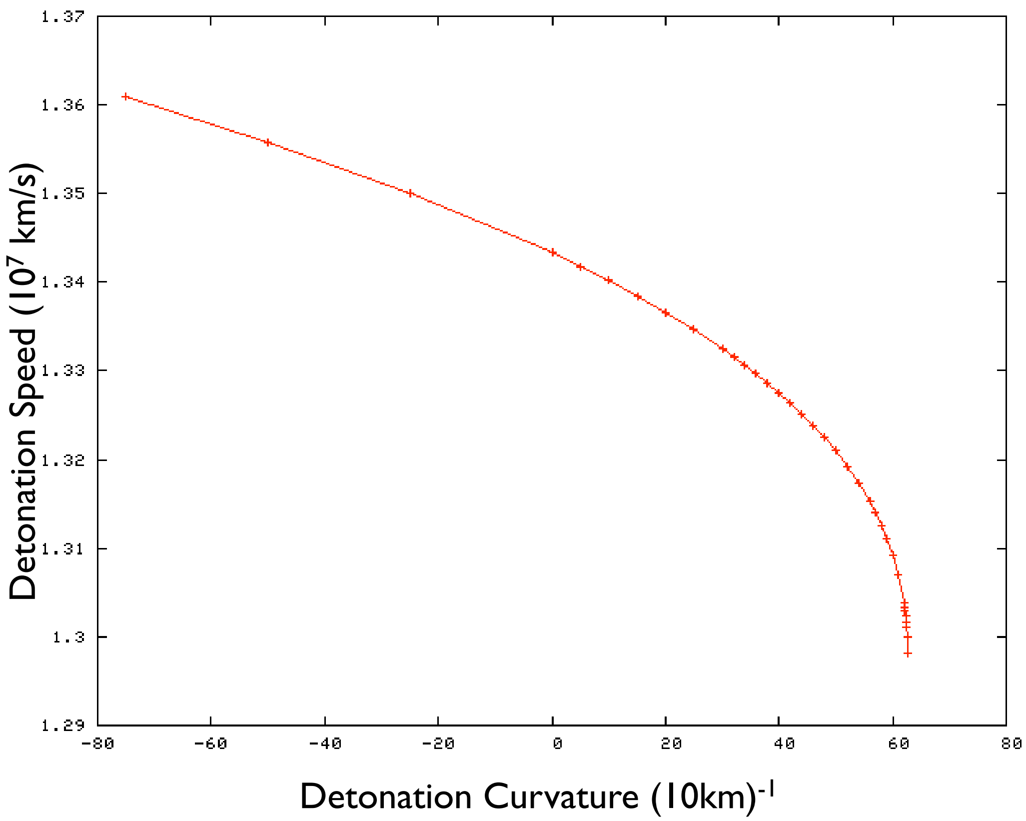
Detonation Ignition

- Ignition at a point -- drives hot shock
- Shock must *slow down* to detonation speed for detonation to ignite
- How big a region? Naively, about a shock thickness $(D\tau_i)$
- About a factor of 5000 too small!



Detonation Ignition

- Curvature strongly modifies detonation
- Speed drops with curvature
- Beyond certain point, no steady detonation.
- Size of region must be ~5000 detonation thicknesses



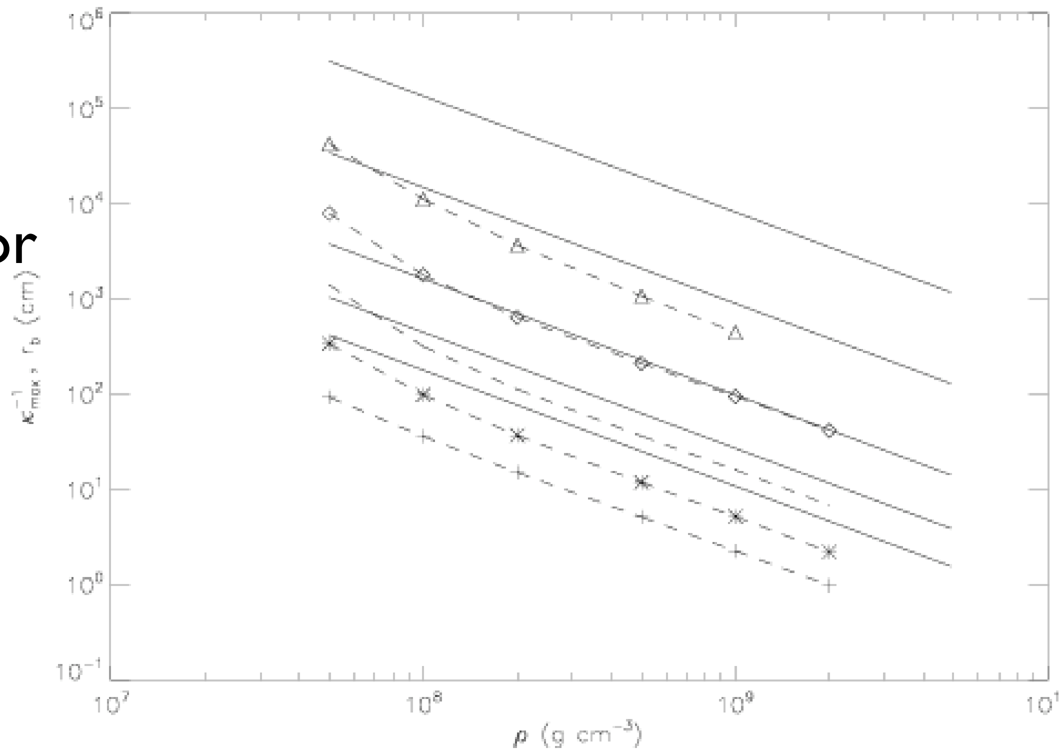
Detonation Ignition

- Corresponding physical size of region grows rapidly with decreasing density

- By 5x10^7, already ~km for low carbon fraction

- **Hard** for purely local process to ignite detonation

- But **very easy** to spuriously numerically ignite detonation



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  - One-zone
  - Flame (ongoing)
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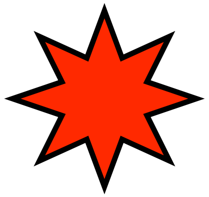
- Early burning: what happens next?
  - Characteristic size of flame bubbles
  - Flame model?

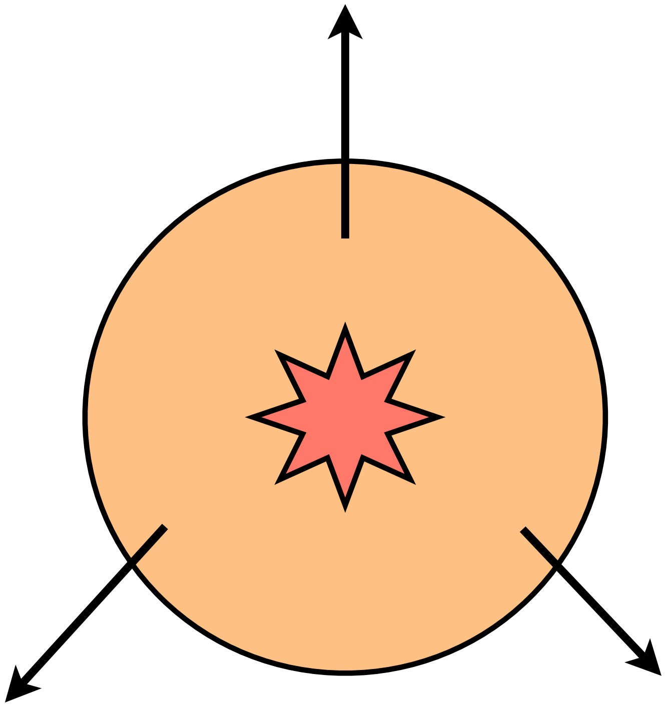
First Burning

- Once a point ignites, what can happen?



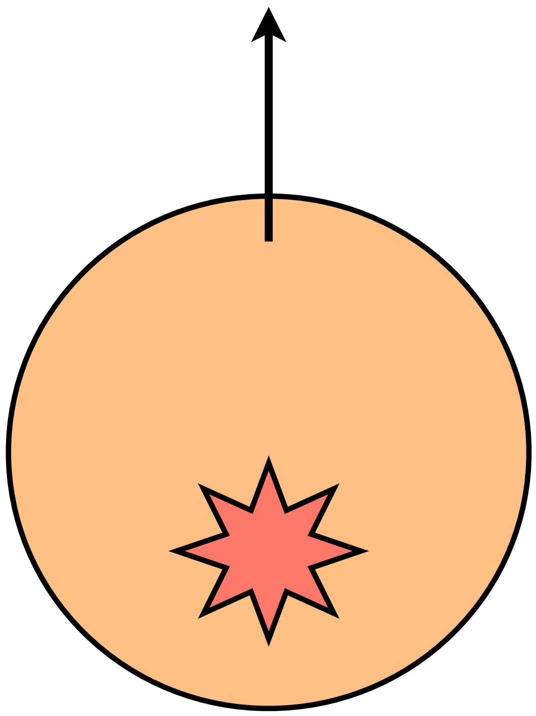
First Burning

- Once a point ignites, what can happen?
  - Spherical flame burning outwards



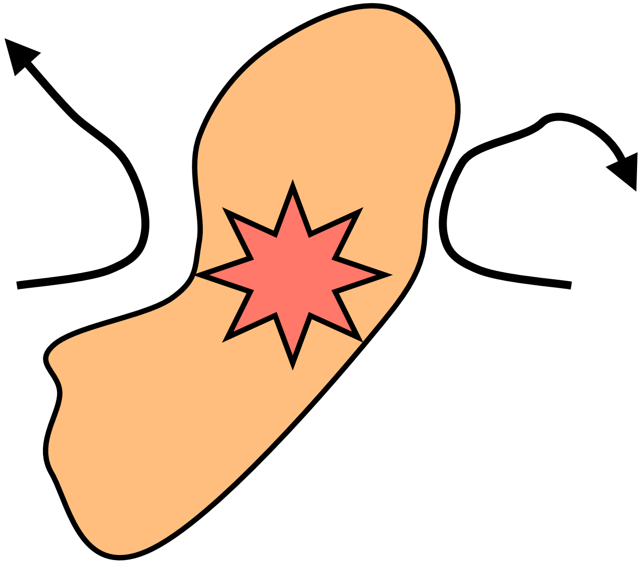
First Burning

- Once a point ignites, what can happen?
  - Buoyant rise



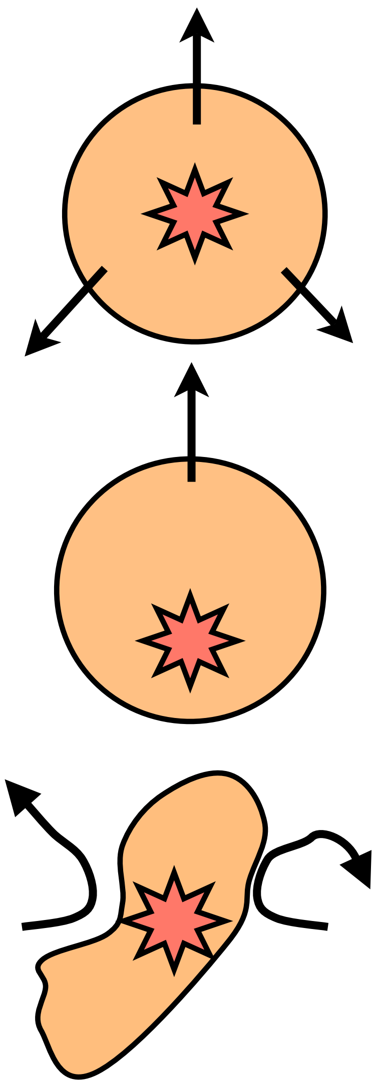
First Burning

- Once a point ignites, what can happen?
  - Distortion by turbulence

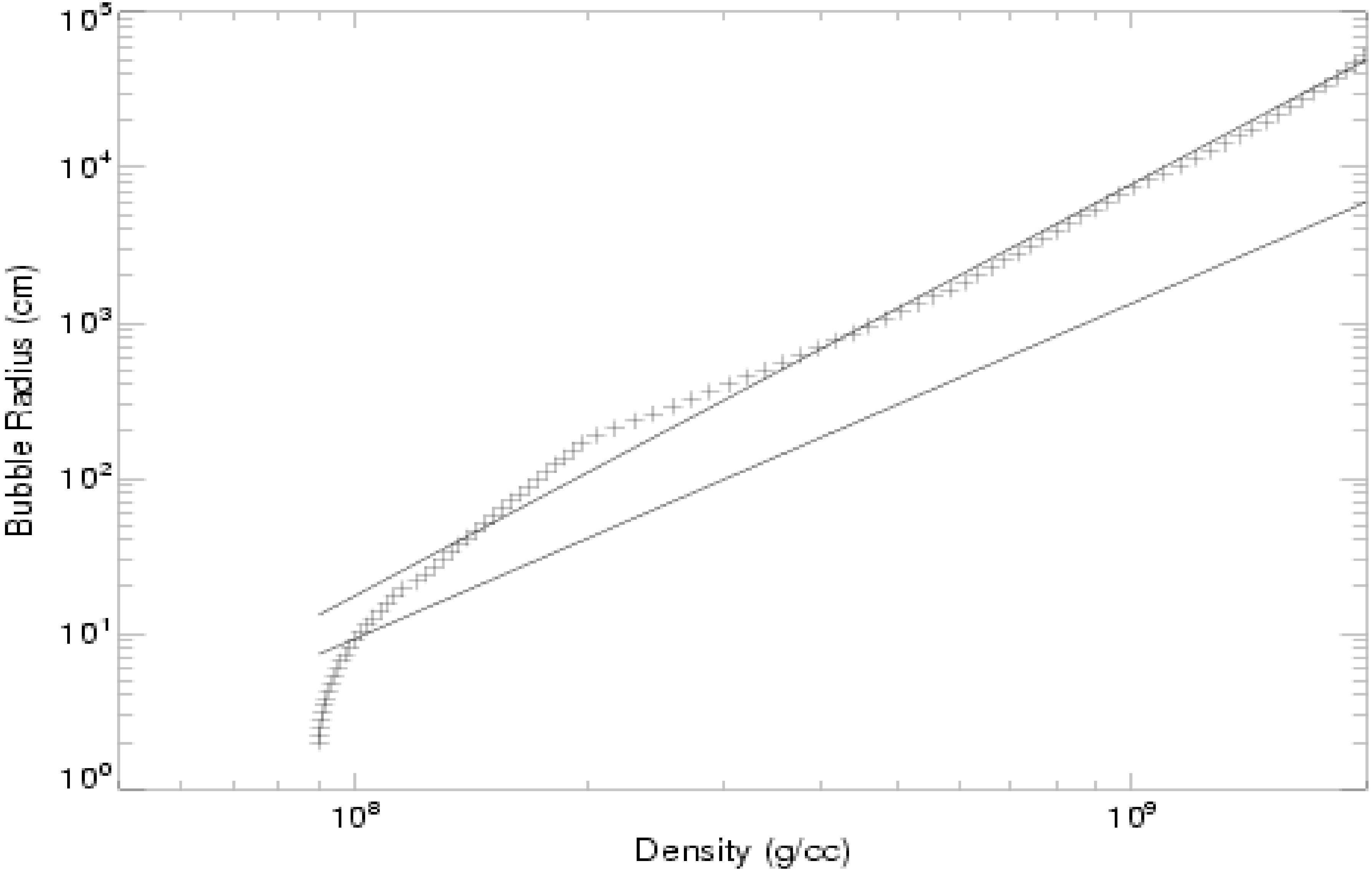


First Burning

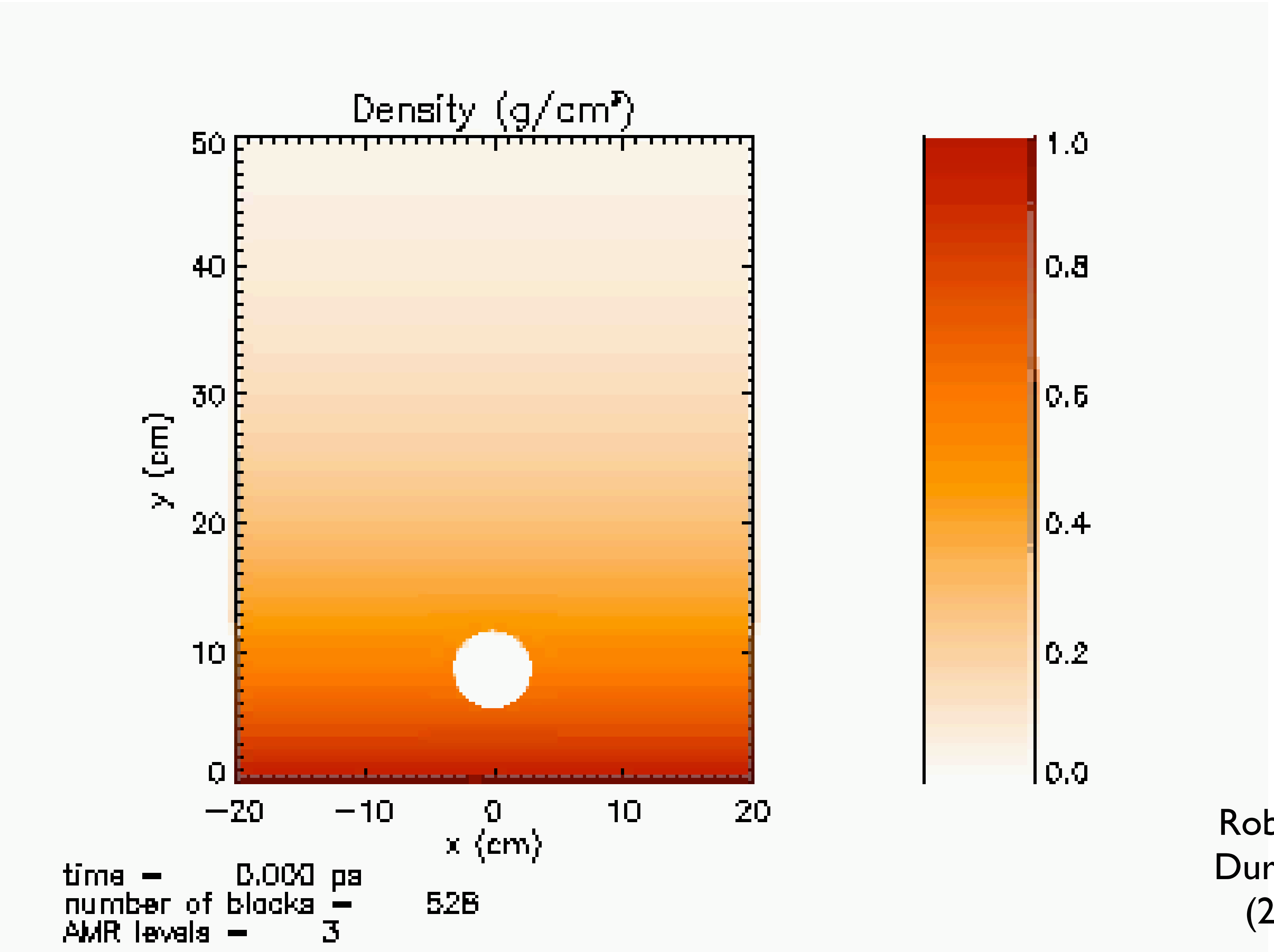
- Each has characteristic velocity
- Flame speed fixed at given dens
- Others bubble-size dependent
- Flame speed always wins until grows



Size where flame speed stops dominating

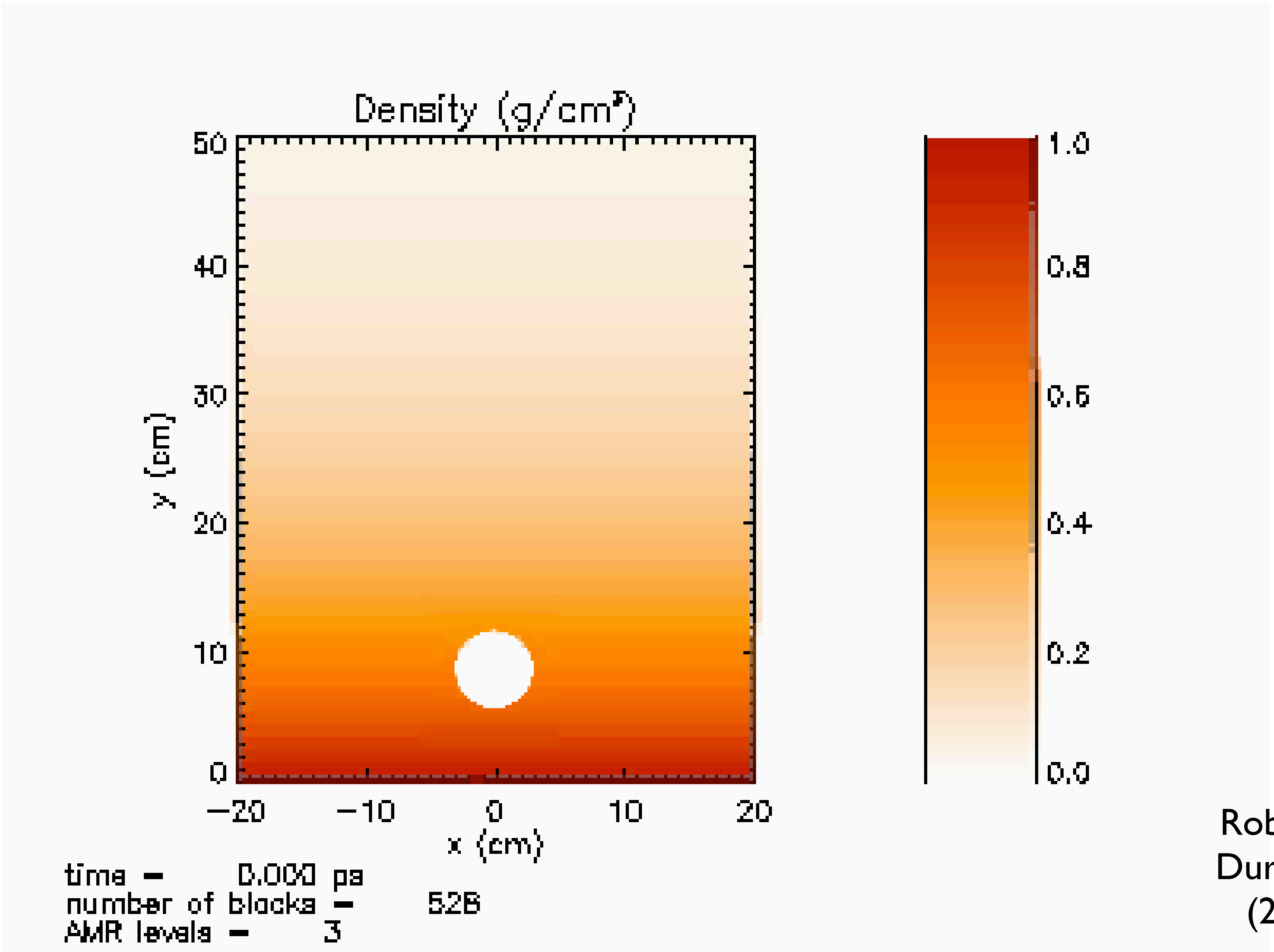


What happens then?

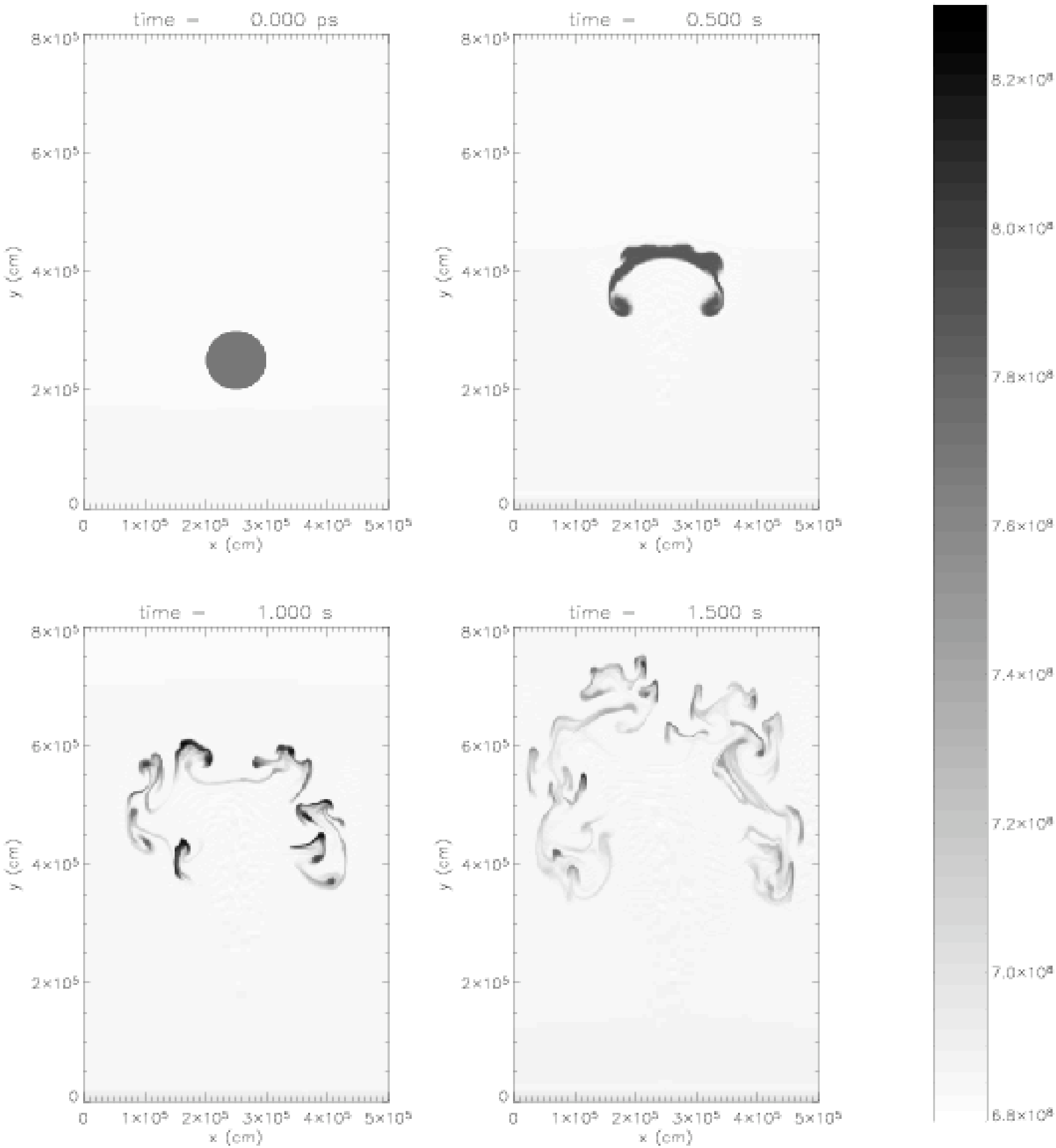


Robinson, Dursi et al (2003)

What happens then?



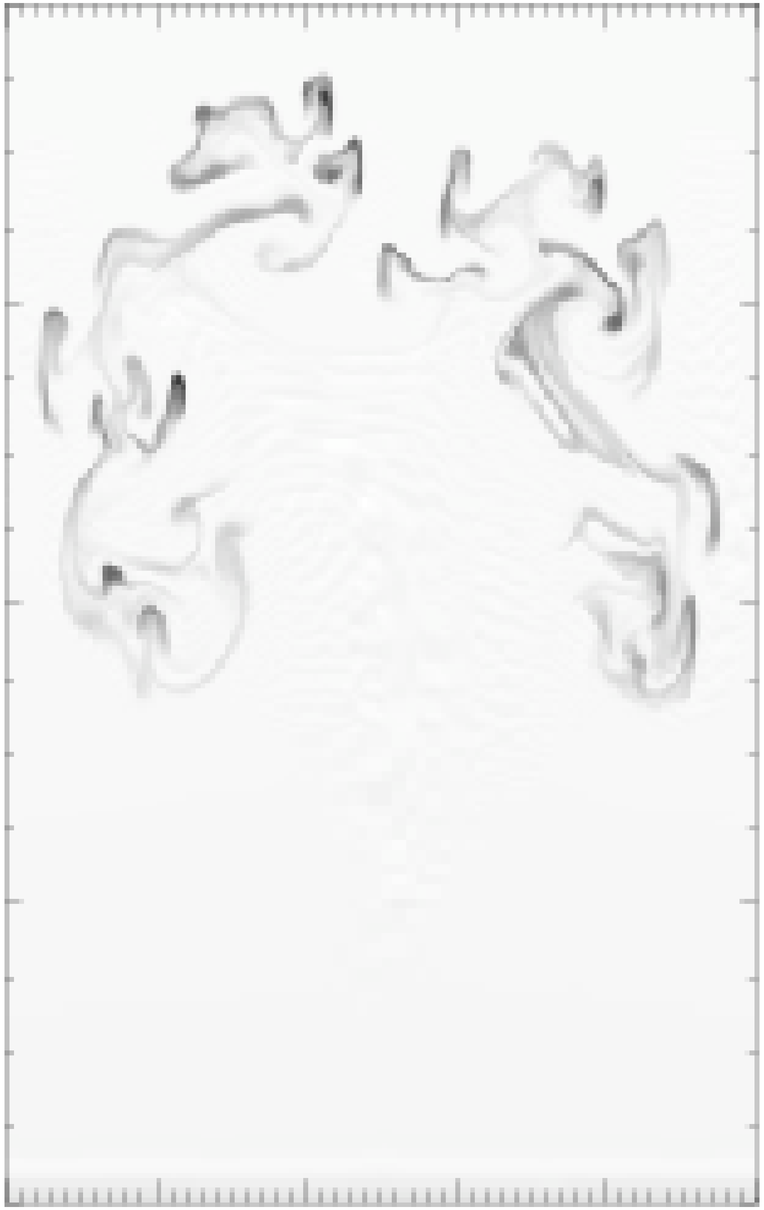
Robinson, Dursi et al (2003)



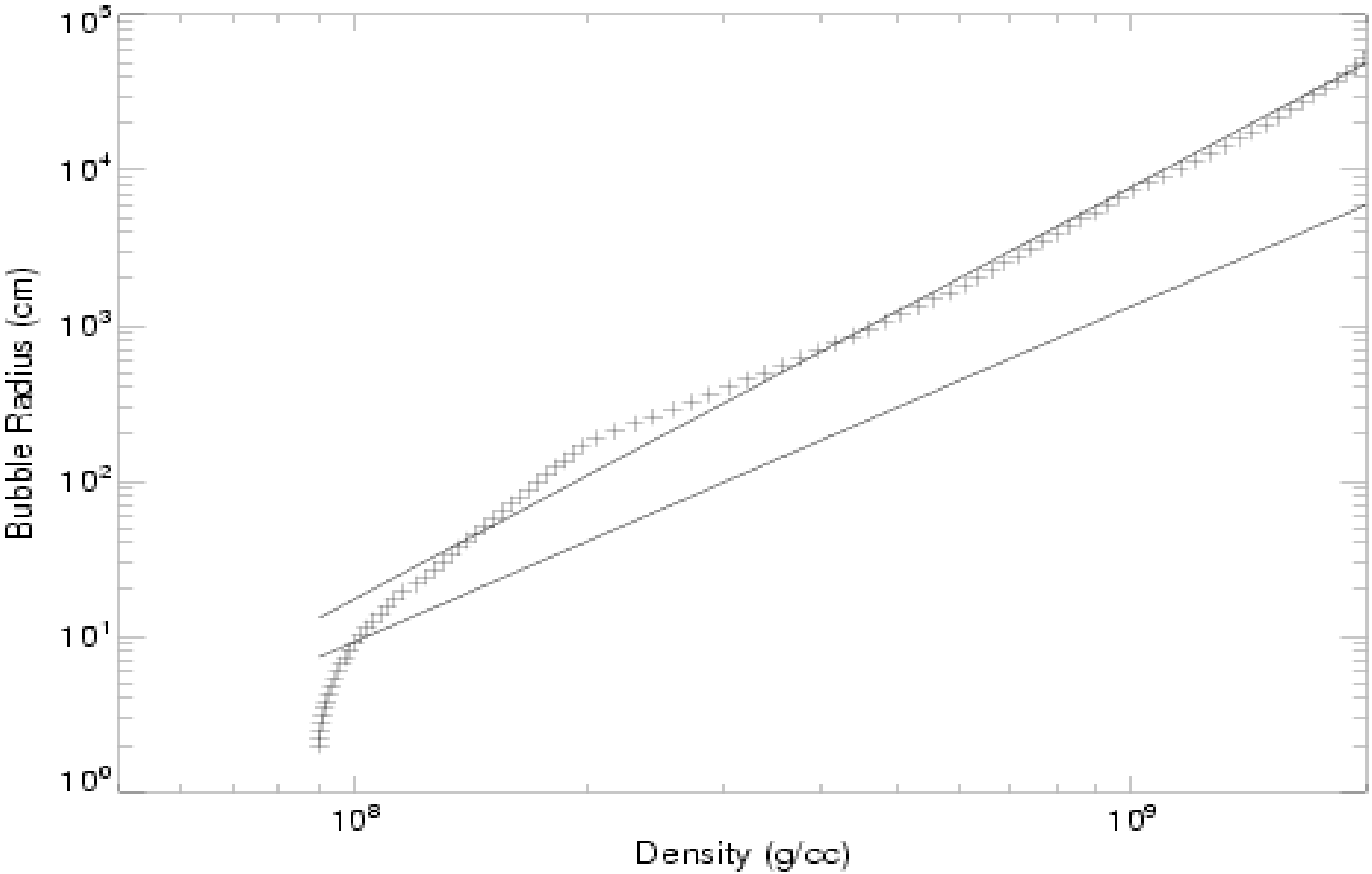
Iapichino et al, (2006)

Buoyant rise

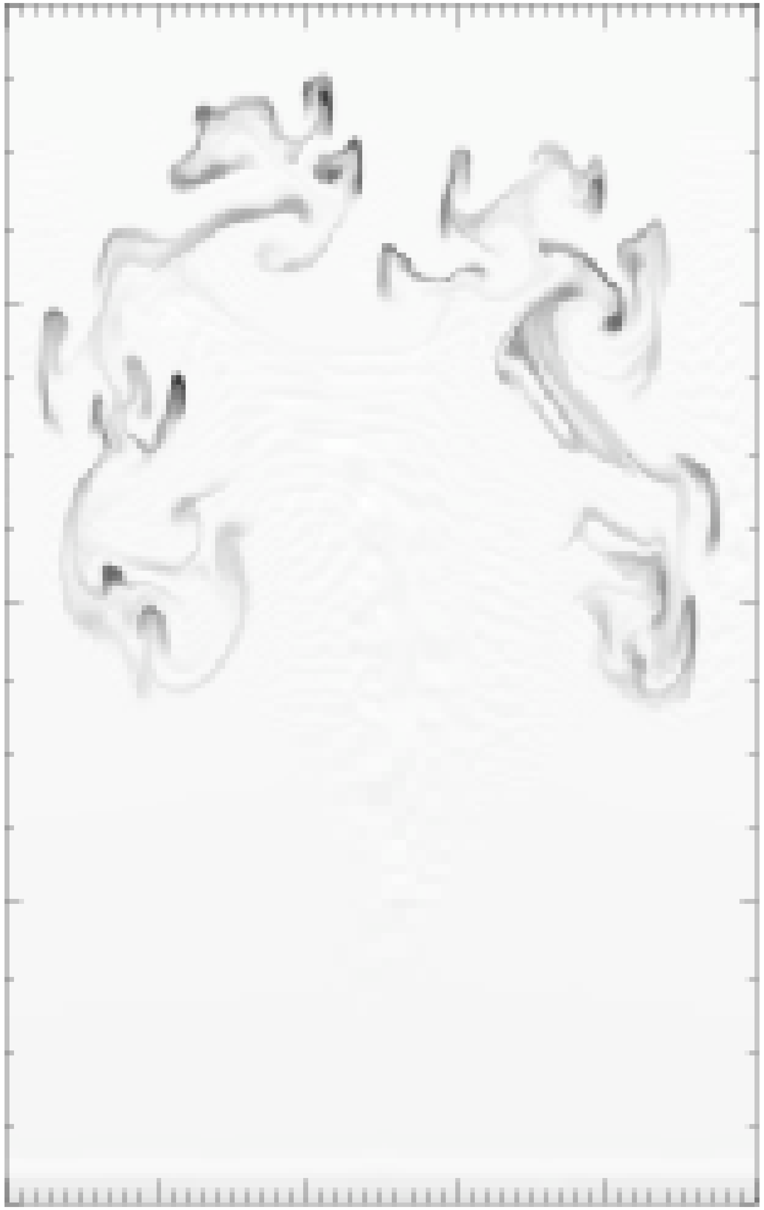
- Vortical motions of bubbles own rise tear it apart
- Unless flame speed is faster
- Balance sets characteristic flame bubble size



Balance between two sets bubble size



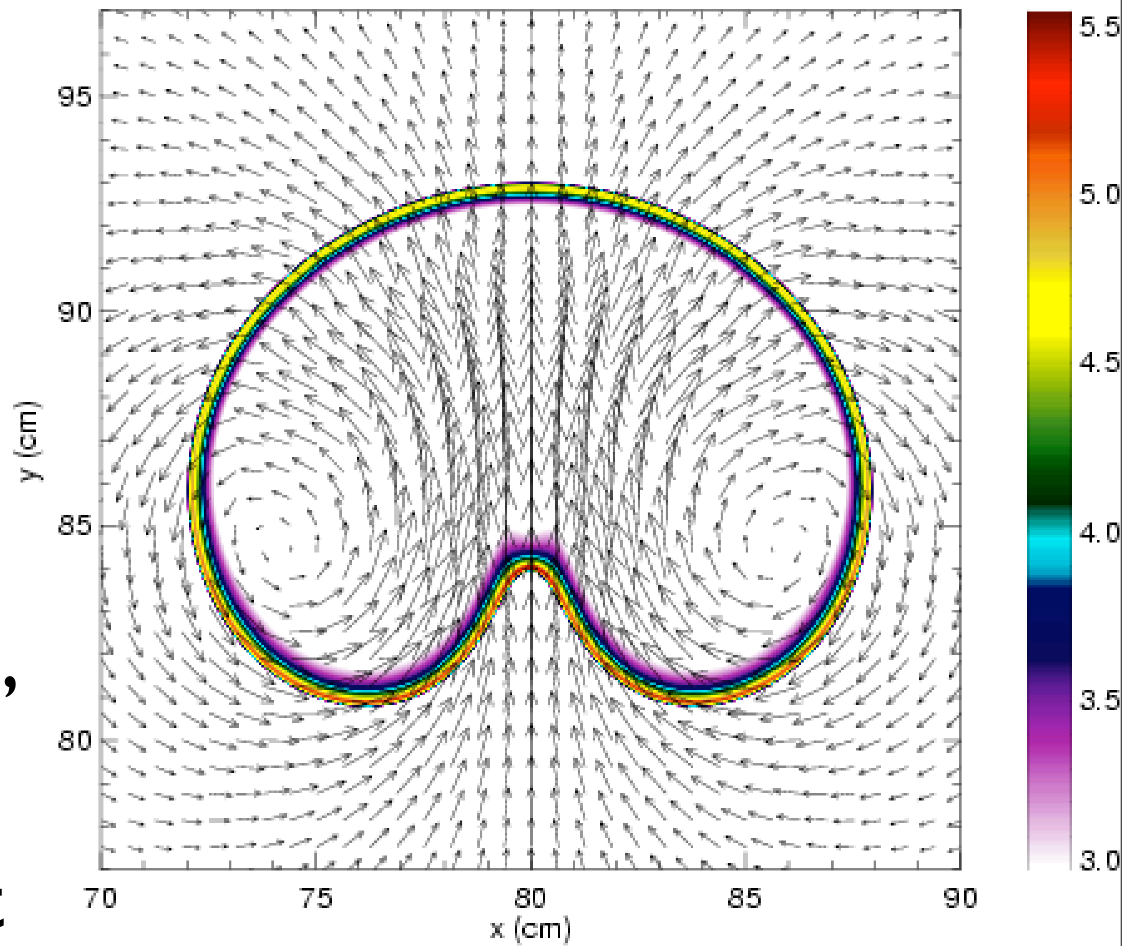
Characteristic bubble Size



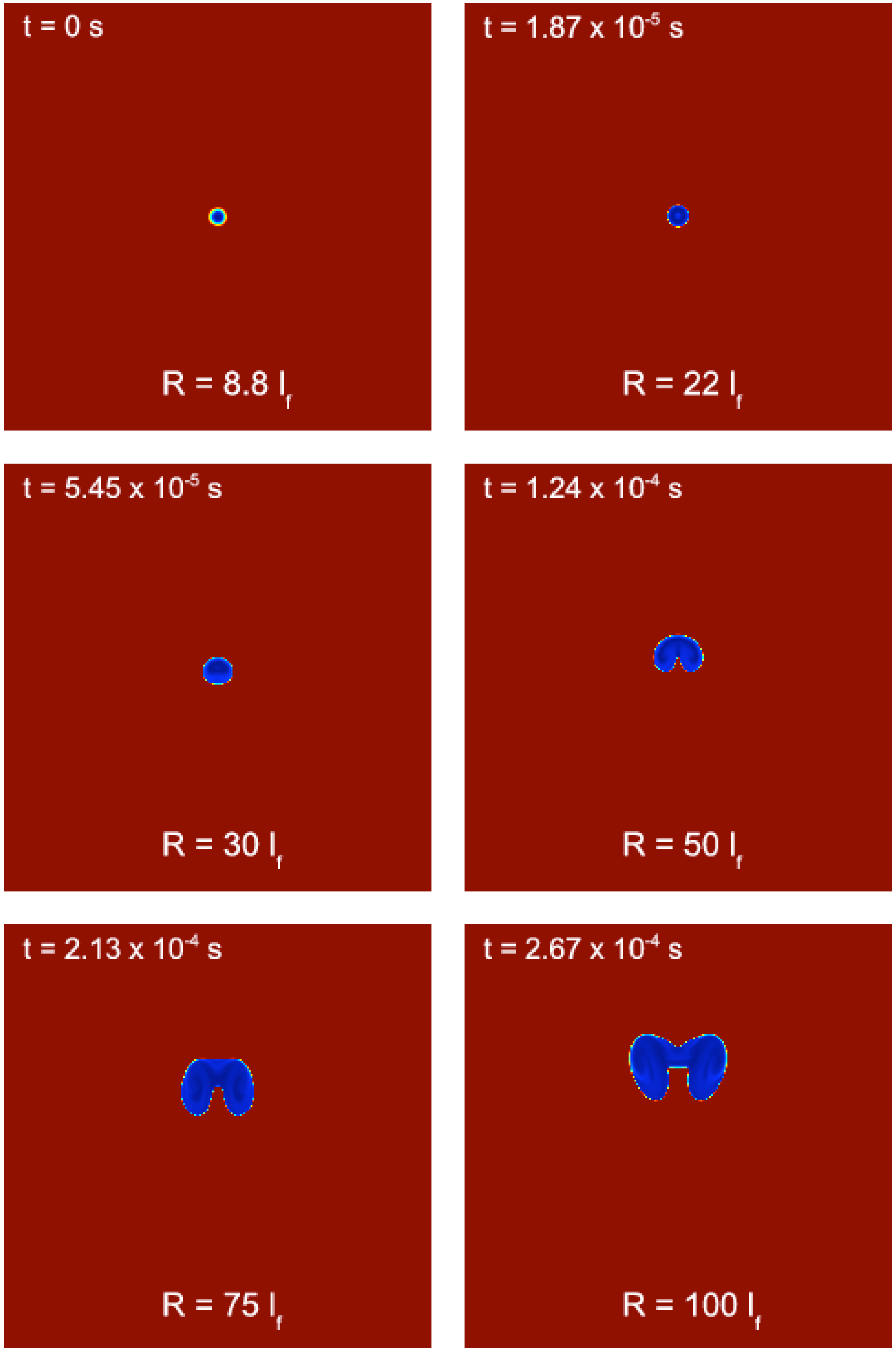
- Sets initial condition `flame bubble' size for large-scale simulation (~0.5 km)

Compared against simulations

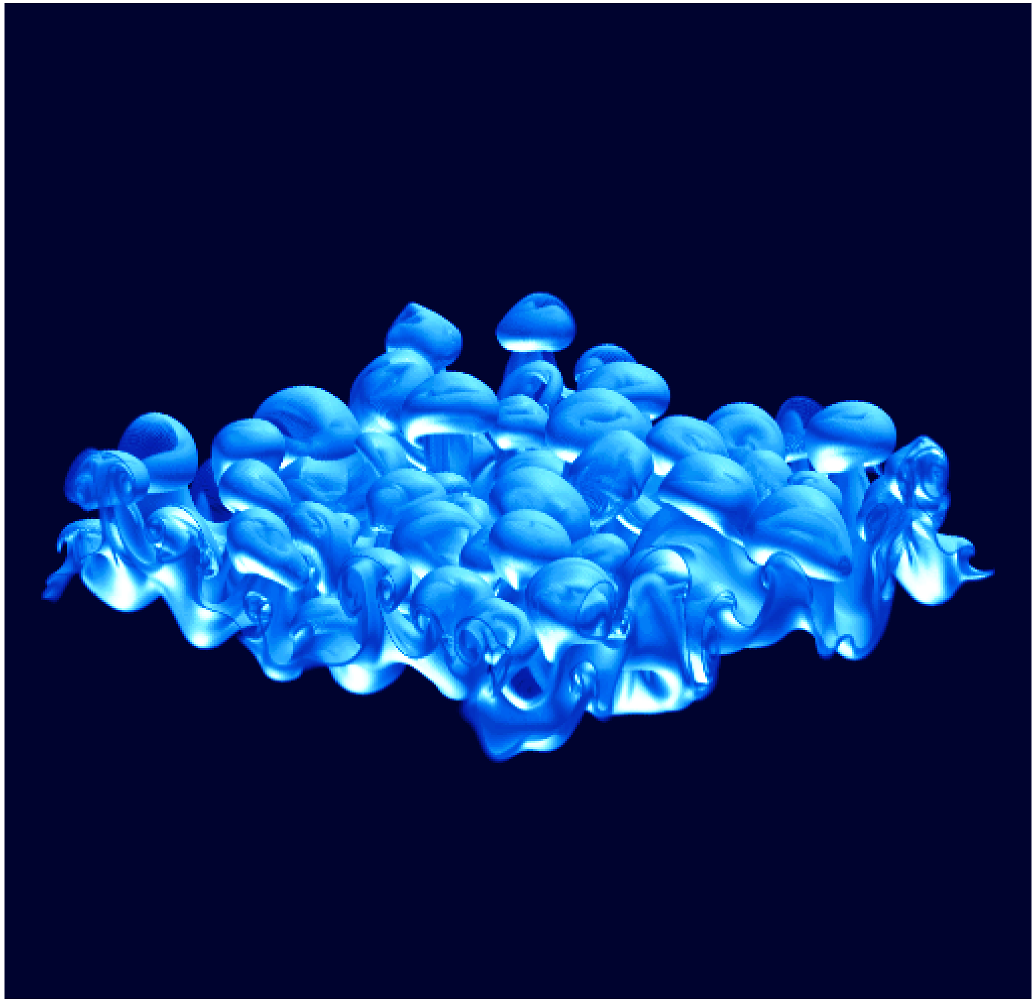
- Semi-analytic calculations comparisons of velocities checked with `real' flame code developed at LBNL (Zingale, Bell, Day, Rendleman)
- Note non-constant flame properties!



- Simple semi-analytic model for this case: flame speed ~ rise speed between 30-50 flame thicknesses in size



Flame modeling



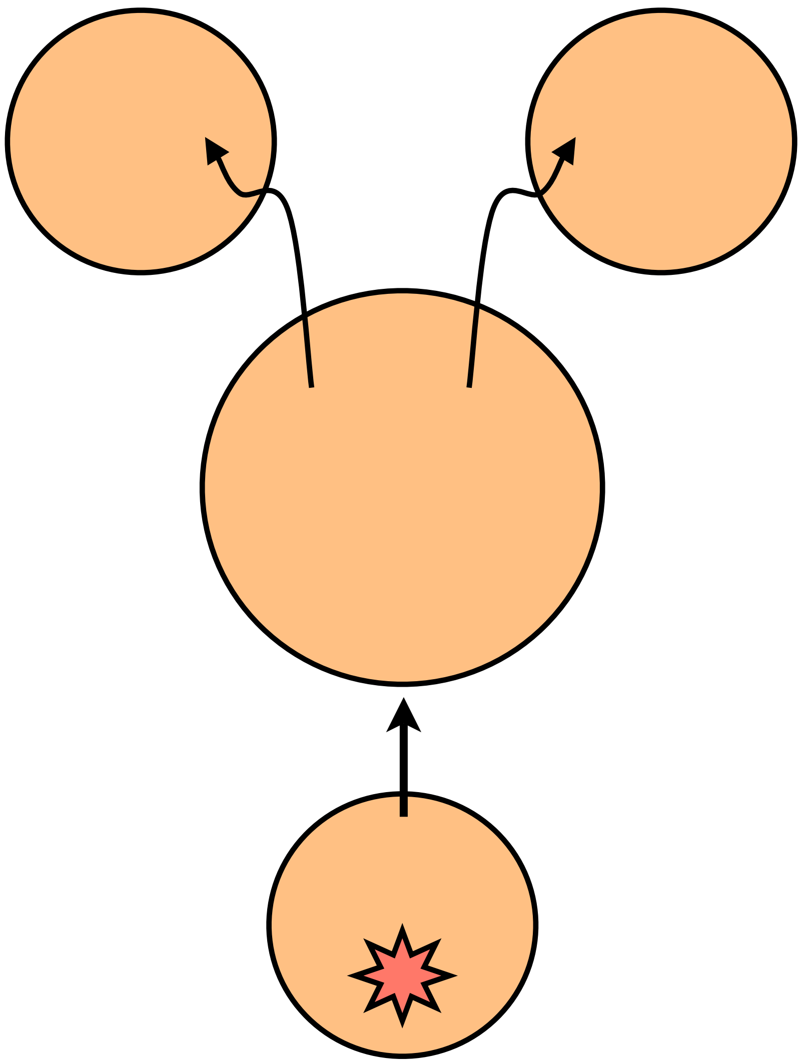
Zingale et al, (2005)

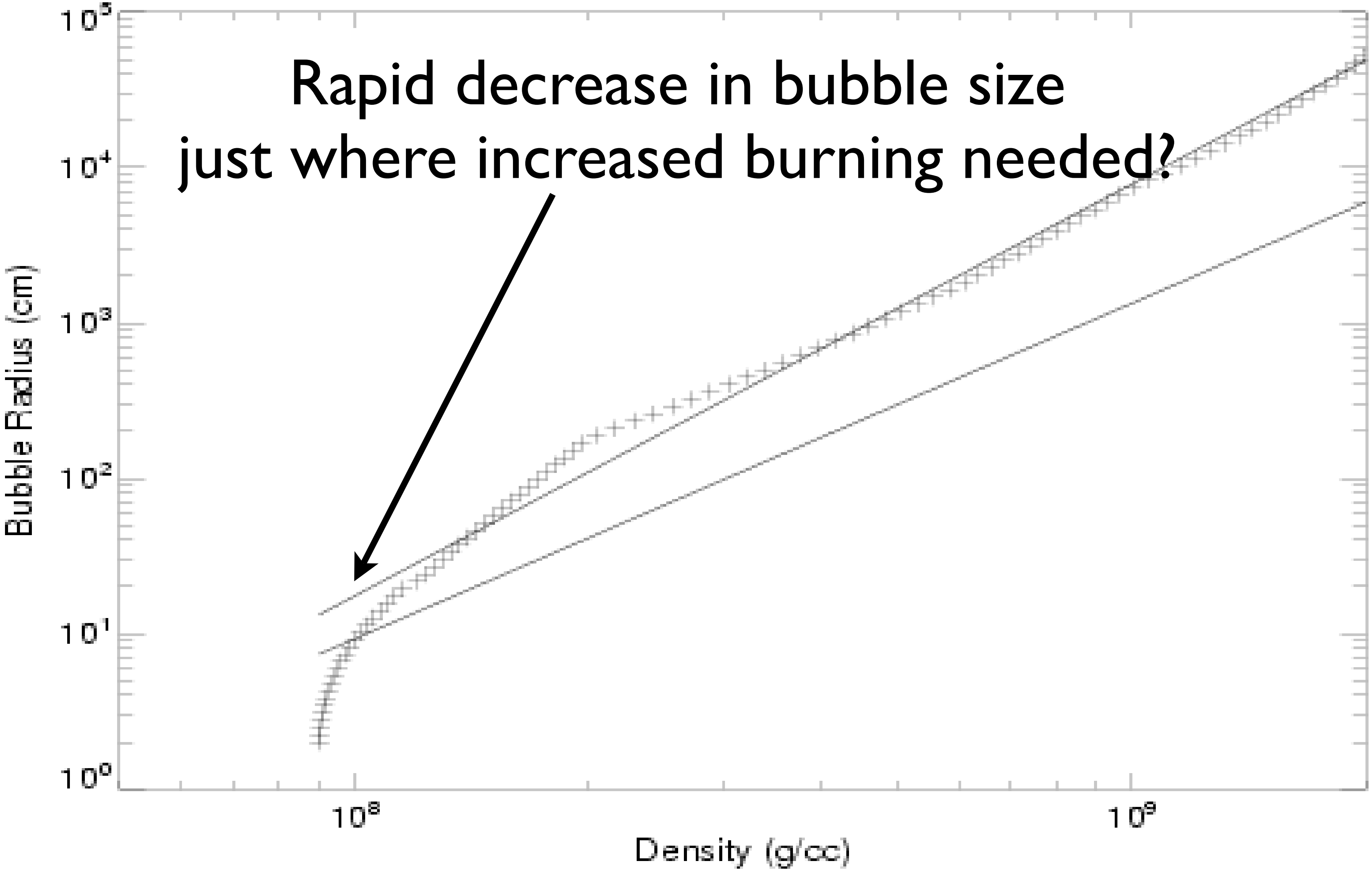
- Flame modeling based on planar picture of flame
- Simulations w/ ~50 flame thicknesses
- Turbulent, RT corrugation
- But much larger range of scales

`Fragmenting Bubbles' Flame Model

- Volume V burning outwards, fragmenting into characteristic volumes

$$\frac{d\mathcal{V}}{dt} = \left(\frac{3\mathcal{V}}{R_f}\right)\dot{R}.$$




Rapid decrease in bubble size
just where increased burning needed?
Bubble Radius (cm)
Density (g/cc)
10^0
10^1
10^2
10^3
10^4
10^5
10^8
10^9

Conclusions

- One zone ignition times - changes w/ Ne
- Hard to ignite detonations
- Flames burn out significantly (~km) before they start to rise
- Initial conditions need roughly this res
- Found typical burning bubble size
- Rapid decrease in size - increased burning?
- Is planar flame model appropriate?

Conclusions

- One zone ignition times - changes w/ Ne
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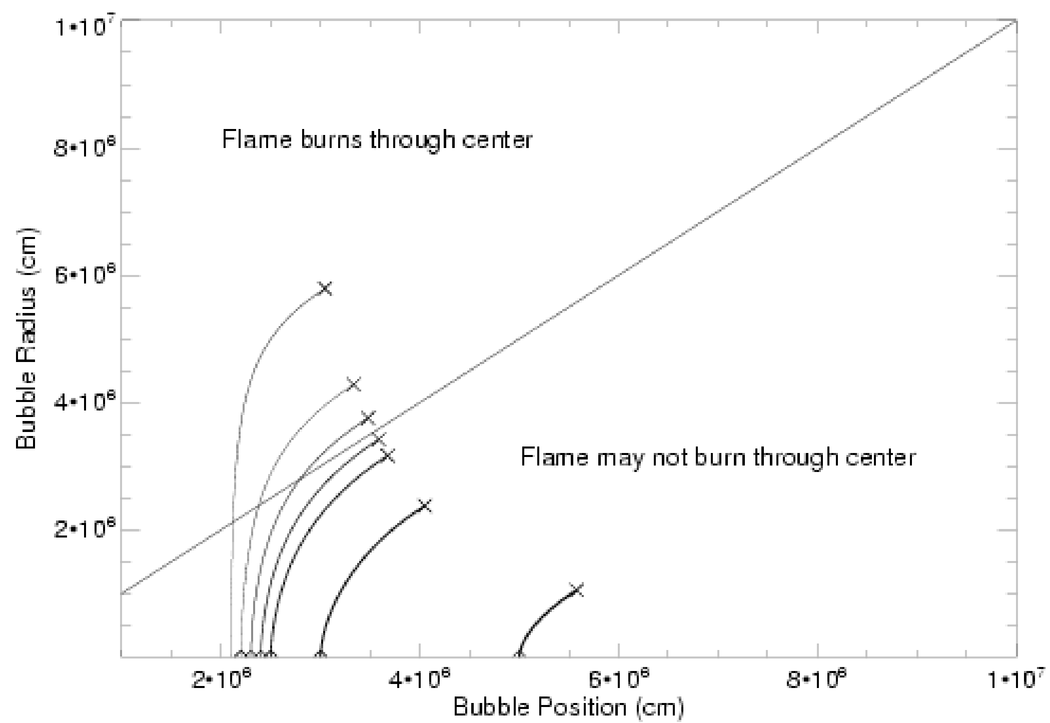
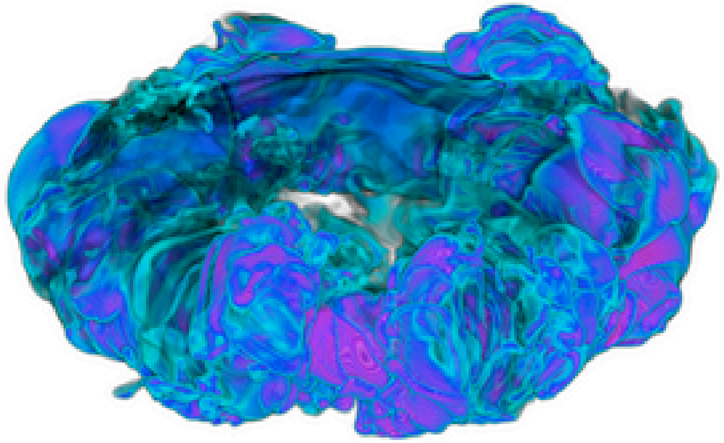
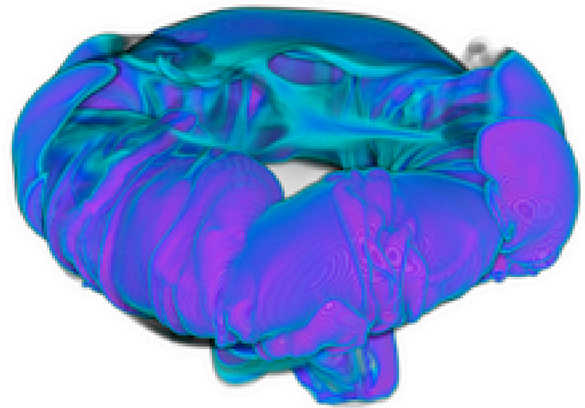
- Flames burn out significantly (~km) before they start to rise
- Initial conditions need roughly this res
- Found typical burning bubble size
- Rapid decrease in size - increased burning?
- Is planar flame model appropriate?

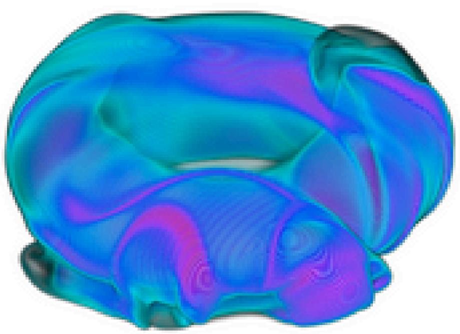
Characteristic Bubble Size

- Can also predict if burns through centre
- If ignites within ~25 km will certainly burn through centre
- No remaining pool of fuel









Zingale et al, (2006)

Sedov ignition of a detonation